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XBT MEASUREMENTS NEAR THE SEA SURFACE: CONSIDERATIONS FOR SATELLITE IR COMPARISONS AND DATA BASES

by

BRIAN WANNAMAKER

15 JANUARY 1980

NORTH ATLANTIC TREATY ORGANIZATION

LA SPEZIA, ITALY

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XBT MEASUREMENTS NEAR THE SEA SURFACE: CONSIDERATIONS FOR SATELLITE IR COMPARISONS AND DATA BASES

by

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XBT MEASUREMENTS NEAR THE SEA SURFACE: CONSIDERATIONS FOR SATELLITE IR COMPARISONS AND DATA BASES

by

Brian Wannamaker

ABSTRACT

Expendable bathythermographs are often used where near-surface information is needed. This study considers the discrepancy between measured and actual temperature profiles in the first few metres of water.

INTRODUCTION

The expendable bathythermograph (XBT) is the most widely used temperature-profiling instrument at present available. The XBT and the airborne version, the AXBT, allow the vertical thermal structure of the ocean to be sampled relatively quickly. The standard shallow-water probe measures a temperature profile (within ± 0.2°C) to a depth of 500 m in 90 seconds. To use the amount of data produced in a survey efficiently a number of digital recording systems have been developed <1 to 4>.

XBTs are routinely launched by naval ships, the measured profiles being used as input to acoustic models and predictions. Rapid XBT surveys are now being used in conjunction with synoptic surface data from orbiting satellites to produce three-dimensional descriptions of oceanic features <5,6,7>.

For both acoustic modelling and merging with satellite data, the accuracy of near-surface temperature measurement is important. The major limitations on accuracy near the sea surface are the time response of the thermistor of the XBT probe and the temperature step across the air/sea interface.

The present study discusses a set of near-surface temperature measurements from XBT probes and from continuously immersed thermistors. Results of considering the XBT as a simple first-order system (RC circuit-like) are also considered under differing conditions.

1 EXPERIMENTAL DATA

During 26 and 27 June 1978, 129 XBTs were launched from the SACLANTCEN research vessel MARIA PAOLINA G. into the Gulf of Cadiz along the track shown in Fig. 1. The launchings were at 15 min intervals and the ship speed was 10 kn (18.5 km/h). Temperature values were sampled by the shipborne computer at 10 samples/second from the digital shaft encoder of the XBT chart recorder (resolution 0.056°C) and stored on digital magnetic tape <1>. Sampling began when the probe entered the water, which completed an electrical circuit with sea return. The data were then transferred to the general-purpose computer for editing, processing, and storage in the data base. During the editing process, 22 records were rejected because of XBT failures.

Continuous analogue chart recordings of temperature from two thermistors were made during the cruise. The first was mounted on a rod lowered through a well in the forward cargo hold to a nominal depth of 4 m. The second extended through the front of a plastic hard-hat filled with buoyant plastic that was towed upside down from a boom 5 m off the starboard bow. This "cappello" thermistor was roughly the same distance behind the bow as the thermistor in the well and in calm conditions was about 5 cm below the surface. During the first half of the experiment it was sometimes affected by the edge of the bow wave because of sea conditions, so its effective depth may have been somewhat greater - say 10 to 50 cm. A longer boom or lower point of support would prevent this interference. Temperature values were read from the charts to the nearest 0.05°C at the times corresponding to the XBT launches. The data were occasionally smoothed when the records were complex. During the second afternoon of the measurements, the temperature records exhibited occasional spikes associated with surface slicks on width scales of about 60 m. Since the XBT spacing was about 5 km, these features were ignored and a smooth line drawn through the thermistor records by eye before readings were taken for comparison.

2 MODELLED XBT RESPONSE

2.1 Assumptions

The time constant of an XBT is given as 0.11 s <1> or as a range of 0.09 to 0.13 s <4>. The fall speed in water is about 6.47 m/s for the shallow-water probe. The launcher of the MARIA PAOLINA G. is about 4.5 m above the surface, resulting in a sea-entry speed of around 9 m/s. If the temperature of the XBT is different from that of the surface water it will be some time before the temperature reading is correct. Starting with the assumption that the XBT responds like a one-stage R-C filter, estimates can be made of the measurement error. Two cases of near-surface temperature profiles will be considered below: isothermal and exponential decrease with depth.

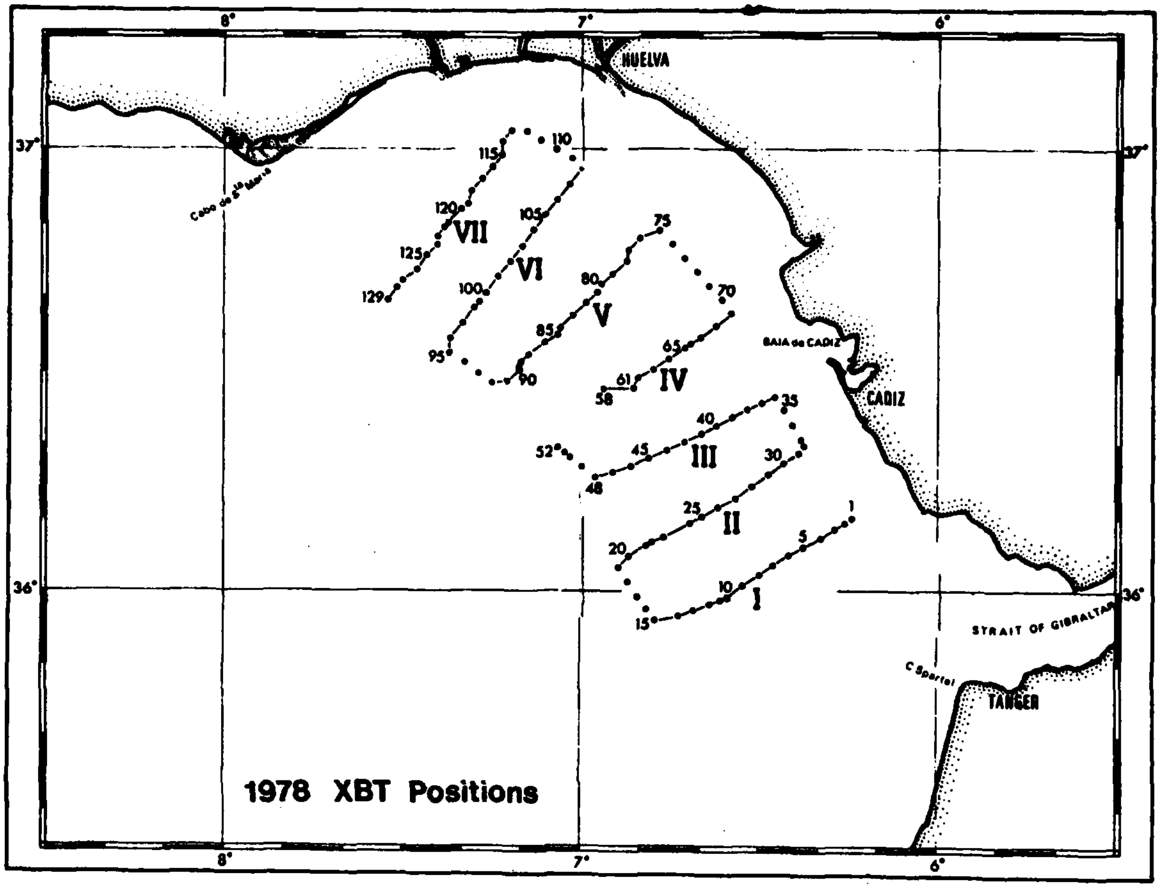

FIG. 1 TRACK OF R/V MARIA PAOLINA G. AND POSITIONS OF XBT LAUNCHINGS JUNE 1978

2.2 Isothermal Profile

When the surface layers are well mixed, the error due to the time response of the thermistor of the XBT probe will depend only on the temperature step across the air/sea interface. This follows the reasonable assumption for this calculation that the probe has equilibrated to air temperature before launch and that the air temperature is constant between the launcher and the sea surface.

After the probe has entered the cooler (warmer) water it will cool (warm) at a rate proportional to the temperature difference between it and its surroundings at any instant

$$\frac{d\theta}{dt} = K(\theta - T_w) \, , \qquad \text{(Eq. 1)}$$

where K is a constant

θ is the temperature reading of the XBT system

T_w is the temperature of the water

t is time in seconds

The differential equation can be solved taking a time constant of 0.11 s and the boundary condition that at t=0, the time when temperature readings begin, the temperature difference is the size of the step across the air/sea interface. The temperature discrepancy at any time can then be written as:

$$(\theta - T_w) = (T_a - T_w)\, e^{-9.1t} \, , \qquad \text{(Eq. 2)}$$

where T_a is the air temperature. The time for the difference to fall within 0.1°C, the precision of the XBT is:

$$t = -\frac{1}{9.1} \ln \left(\frac{0.1}{T_a - T_w}\right) \qquad \text{(Eq. 3)}$$

The depth of the shallow-water (500 m) XBTs in metres is calculated from

$$d = 6.472\, t - 0.00216\, t^2 \qquad \text{(Eq. 4)}$$

The second-order term can be ignored above 10 m depth.

Table 1 lists the depths calculated from Eqs. 3 and 4 for various temperature steps. Also shown are the values when time constants 0.90 s and 0.13 s are used. Figure 2 illustrates expected XBT output traces for some of the temperature steps in Table 1. For common temperature steps of less than 5°C, the XBT reading should be within the ±0.1°C precision after about 2 to 3 m depth. However, the temperature profile is often more complex than this.

TABLE 1

DEPTH AT WHICH THE TEMPERATURE READING OF AN XBT
(initially at air temperature)
IS WITHIN 0.1°C OF A CONSTANT WATER TEMPERATURE FOR DIFFERENT
AIR/SEA TEMPERATURE STEPS AND XBT TIME CONSTANTS

(Air Temp. - Sea Temp.) (°C)	Depth (m) Time constant (s) 0.09	0.11	0.13
0 ± 0.1	0	0	0
± 0.2	0.4	0.5	0.6
± 0.5	0.9	1.1	1.4
± 1.0	1.3	1.6	1.9
± 2.0	1.7	2.1	2.5
± 5.0	2.3	2.8	3.3
± 10.0	2.7	3.3	3.9

2.3 Exponential Profile

In the absence of surface mixing, the sea temperature may decrease approximately exponentially in the top metre or few metres. On the second day of this experiment, the difference in temperature measured by the "cappello" thermistor near the surface (at about 5 cm) and the well thermistor at 4 m was as much as 3°C (Fig. 5).

The exponential decay of temperature can be described by

$$T_w = T + \Delta T = T + \Delta T_o \, e^{-K_1 d} \ , \qquad \text{(Eq. 5)}$$

where T = temperature of the mixed layer below the exponential profile

ΔT_0 = difference between the surface temperature and T

d = depth

Assuming that the temperature at 4 m is within 0.01 ΔT_o of T,

$$K_1 = -\frac{1}{4} \ln (0.01) \ . \qquad \text{(Eq. 6)}$$

To model the XBT response, the water is assumed to be divided into 5 cm thick isothermal layers. The XBT reading is then calculated using Eq. 2 in each layer, with depth replacing time according to Eq. 5. Figure 3 illustrates expected XBT reading for various magnitudes of air/sea tempe-

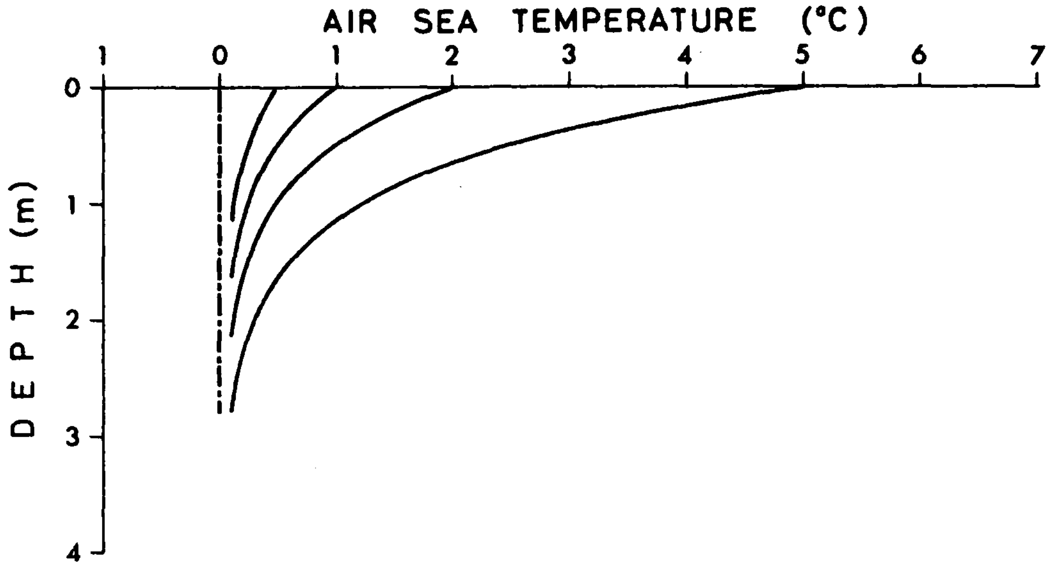

FIG. 2 MODELLED XBT RESPONSES (solid lines) WHEN ENTERING WATER WITH AN ISOTHERMAL TEMPERATURE PROFILE (chain line)

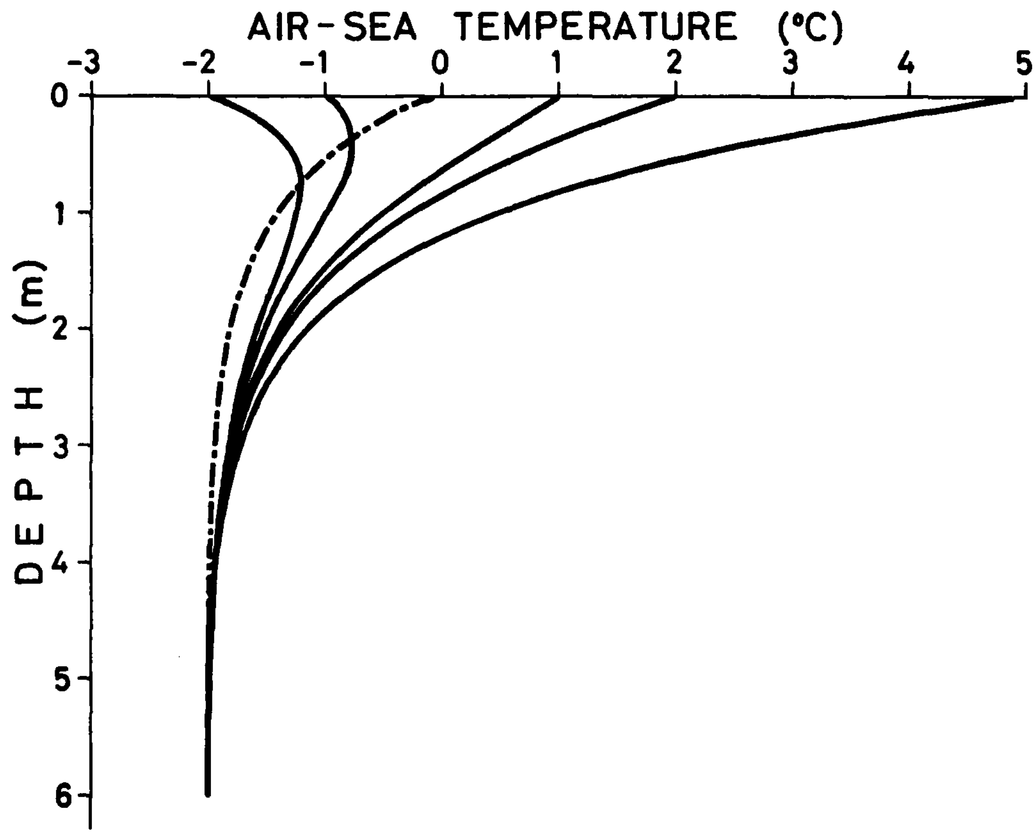

FIG. 3 MODELLED XBT RESPONSE (solid line) WHEN ENTERING WATER WITH AN EXPONENTIAL TEMPERATURE PROFILE (chain line)

rature steps for an exponential temperature profile that diminishes by 2° from the surface value. Under these conditions the depth at which the measured value is within 0.1°C of the true value is 3 to 4 m.

3 IN-SITU DATA

Figure 4 shows XBT surface temperatures and the corresponding values from the "cappello" thermistor. The former are always higher than the latter. Some of the cruise legs last longer than others because of shipboard operations. On the first day the wind speed was 15 to 20 kn (8 to 11 m/s) while on the afternoon of the second day the wind had dropped to below 8 kn and the sea was calm.

Figure 5 illustrates the difference between the water temperature measured by the "cappello" (nominally 5 cm depth) and the well (nominally 4 m depth) thermistors. It is apparent that the measurements can be divided into two categories. Initially the temperature difference is very small and it can be assumed that the water down to 4 m depth is isothermal. Taking differences of greater than 0.5°C as indicative of stratification, this occurs between 1000 and 1900 GMT on day 2. For modelling purposes this stratification has been assumed to be exponential. This is felt to be reasonable under the conditions of strong solar input from clear skies into a calm sea. During this time the mean value of the difference in sea-surface temperature estimates from the XBTs and "cappello" thermistor (see Fig. 4) decreases to -0.5°C (standard deviation $\sigma = 0.8°$) compared with the overall mean of -0.7°C ($\sigma = 0.6°$). There are outliers from this trend: two of the differences are greater than -2°C. This may be the result of the XBTs lying in the sun before use. At times the surface water may more closely approach air temperature; an XBT may then give a good estimate of sea-surface temperature but not be able to react quickly enough to follow the temperature profile immediately below that.

Figure 6 shows the temperature of the well thermistor at 4 m depth and the value from the XBT record for the first depth value greater than 3.7 m. The XBT data were sampled at about 0.65 m separation, and interpolation is not justified because of the vertical movement of the well thermistor by the ship's motion. From the consideration of the time constant in the previous chapter it was suggested that under exponentially stratified conditions the XBT reading could still be above the true value at 4 m depth. In the experimental values, the mean value of the difference (XBT - well temperature) under stratified conditions is 0.3°C ($\sigma = 0.12$°C). Under well-mixed conditions the mean value of the difference was 0.18°C ($\sigma = 0.16$°C). This is significantly lower than the former value at the 99% confidence level of the 't' distribution. The latter value may be taken as the bias between the instrument systems, which were not calibrated with respect to each other.

Figure 7 shows the results of fitting the modelled XBT response to a few of the XBT records. In 7a, isothermal conditions were assumed because of the small differences between "cappello" and well temperatures; the initial XBT

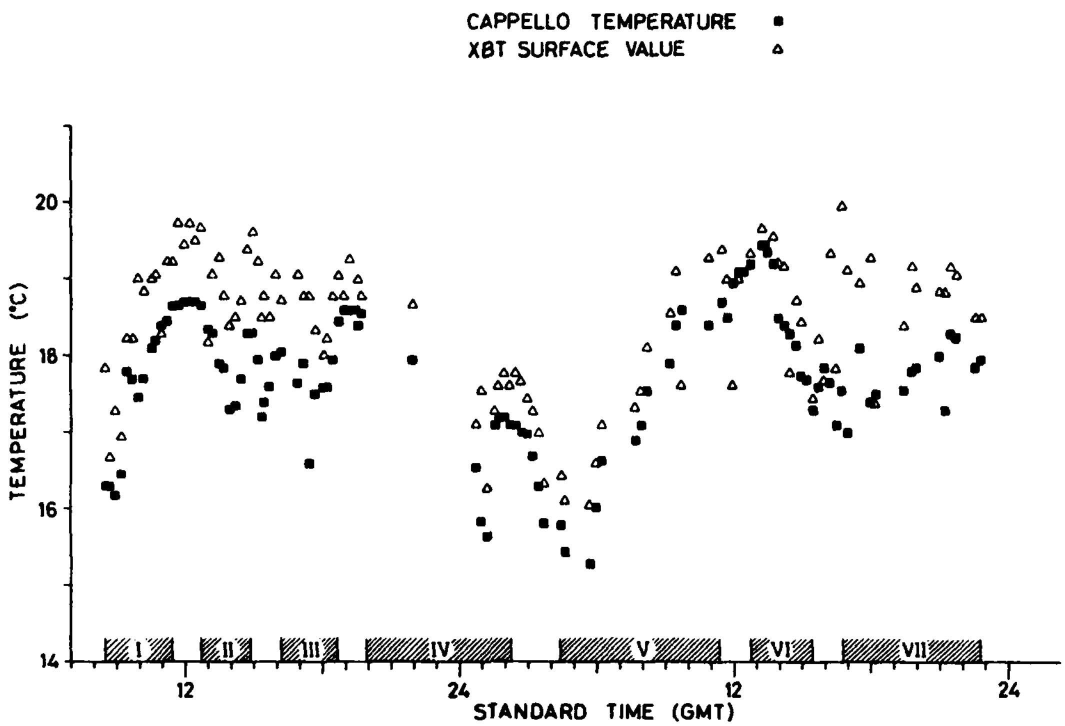

FIG. 4 SEA-SURFACE TEMPERATURE MEASURED BY THE XBTs AND THE "CAPPELLO" THERMISTOR (nominally 5 cm below surface). The numbered bars indicate the duration and number of the cruise leg as shown in Fig. 1

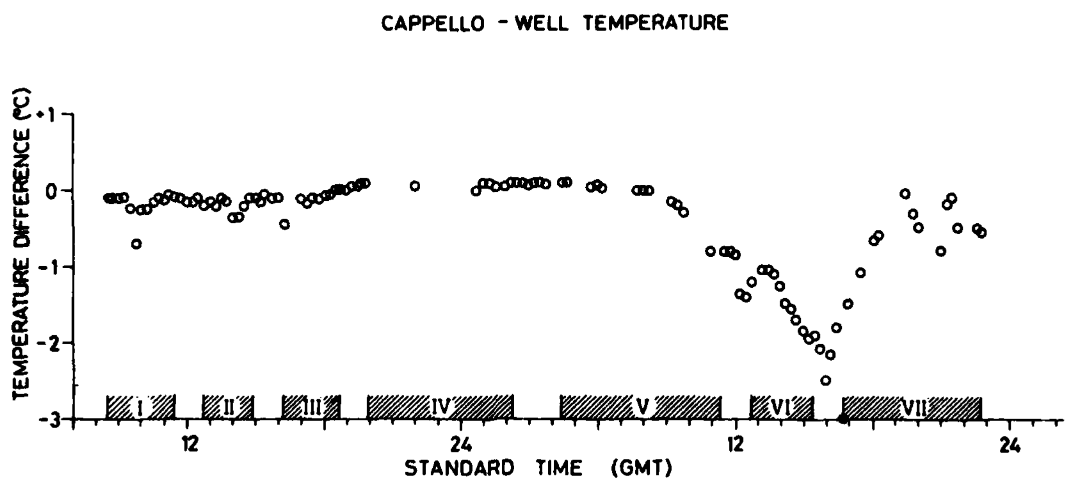

FIG. 5 THE WATER-TEMPERATURE DIFFERENCE BETWEEN ABOUT 5 cm DEPTH ("cappello") AND ABOUT 4 m DEPTH (well) MEASURED BY IN-SITU THERMISTORS

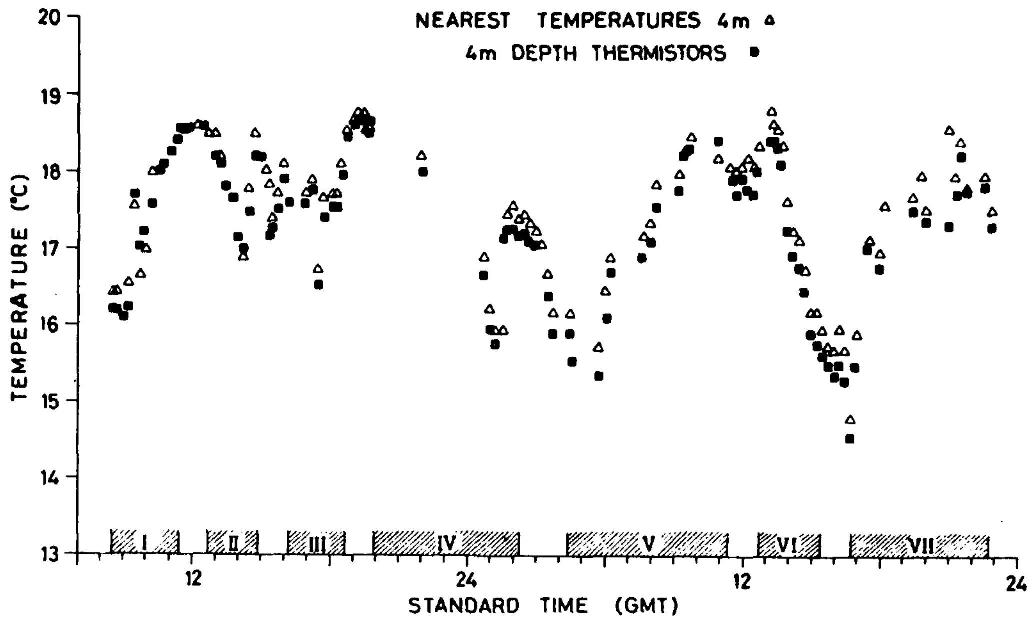

FIG. 6 WATER TEMPERATURE AT A NOMINAL DEPTH OF 4 m MEASURED BY IN-SITU THERMISTORS (well) AND XBT

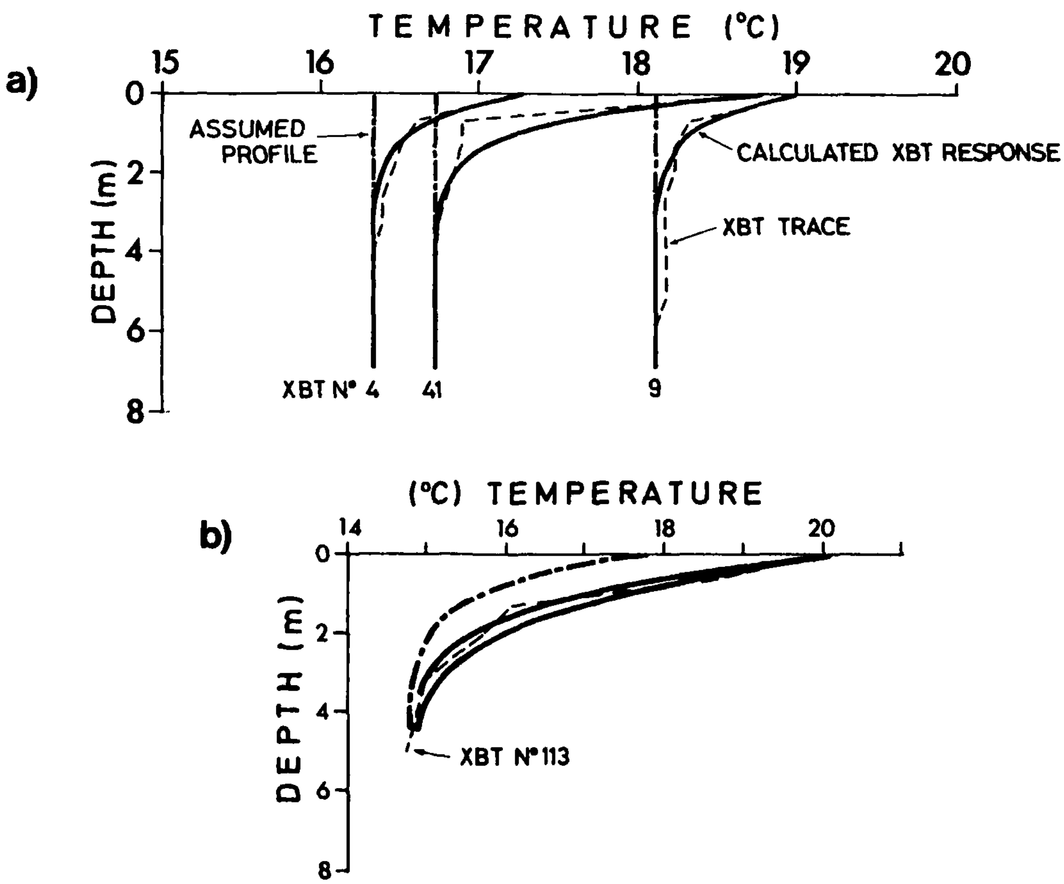

FIG. 7 COMPARISON OF MODELLED (solid line) AND RECORDED (dashed line) XBT RESPONSES FOR ASSUMED ACTUAL PROFILES (chain line). In (a) an isothermal profile is assumed; in (b) an exponential profile. The two calculated profiles in (b) are at the extremes of the specified time constants. The XBT values were recorded with a least-count precision of 0.056°C at 10 samples/second

value was taken as air temperature. General agreement is shown, with the measured values falling off more quickly at first and then more slowly than the first-order curve. This may be partially due to the depth of the first non-surface values of the XBT being underestimated because the enetry speed is greater than 6.47 m/s. However, the model is meant as an indicator of the relationship rather than as a basis for deconvolution. Figure 7b shows a fit to an exponential profile, with two calculated curves corresponding to time constants of 0.09 s and 0.13 s. Again the fit is generally good, indicating that the estimates of depths for which the XBT reading is within the 0.1°C precision are reasonable.

4 CORRECTIONS FOR DATA-BASE USAGE

It is expected that all future XBT data digitally recorded on the R/V MARIA PAOLINA G. will be entered into the SACLANTCEN data base <8>. The poor information in the near-surface water may be ignored or replaced by a slightly better estimate of the profile. When XBTs are digitized from the chart records, FNWC (U.S.Fleet Numerical Weather Central) procedure has been to extrapolate the record back up to the surface from 8 ft (2.4 m), using the slope at that depth <9>.

From the information presented in the previous chapter, it was decided to extrapolate back from 4 m by using the slope between 6 and 4 m. Each automatically corrected record was visually screened and obvious errors due to extrapolation were corrected manually. Six percent of the 107 XBTs were corrected in this way. Figure 8 compares the "cappello" and XBT values after the corrections. The mean difference was reduced from 0.71°C ($\sigma = 0.6°$) to -0.08°C ($\sigma = 0.6°$). The greatest discrepancy occurs during the time of large differences in the "cappello" and well measurements (afternoon conditions) when the extrapolation underestimates the true value. This was felt to be acceptable for data-base purposes, where they are to be used for synoptic scale analysis.

CONCLUSIONS

The XBT has been modelled as a one-stage R-C response system to check the effect of the time response of near-surface measurements for air/sea temperature differences greater than 1°C. From this it was inferred that the discrepancy in the measurement was greater than the probe's precision (0.1°C) in the upper 2 to 3 m with an isothermal water profile and in the upper 3 to 4 m with stratified conditions.

The near-surface data from 107 XBTs have been compared with data from continuously immersed thermistors at about 0.05 and 4 m depth. At 4 m the discrepancy between the XBT and continuous measurements was 0.12°C greater in stratified conditions than in well-mixed conditions.

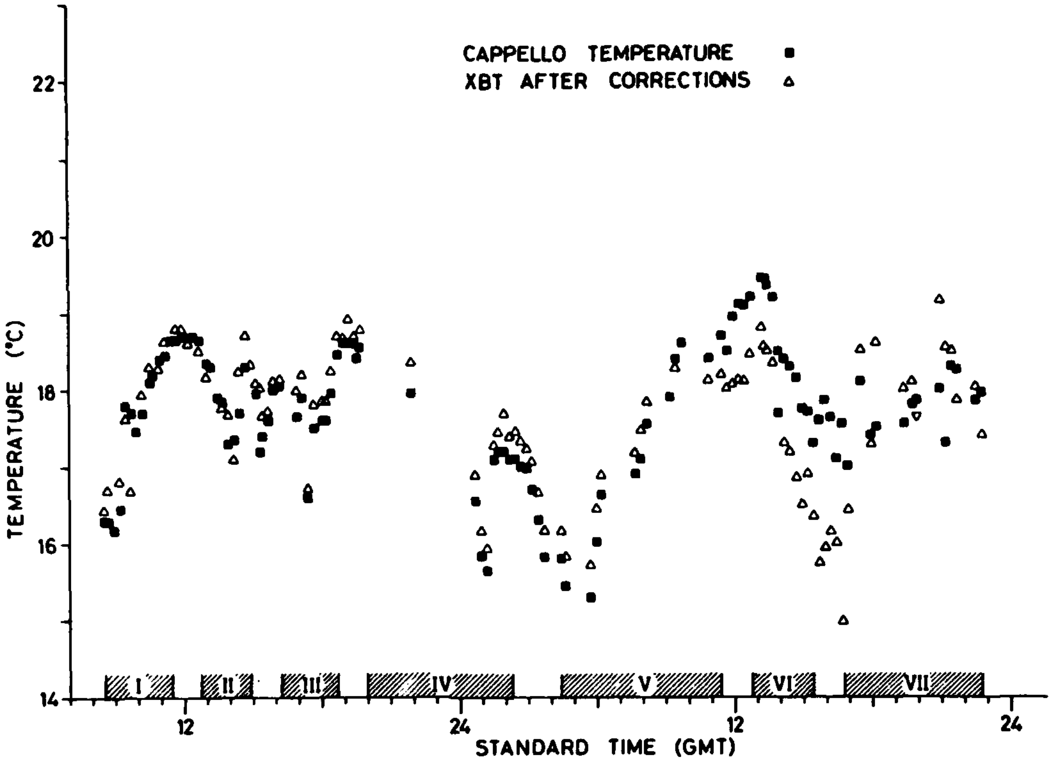

FIG. 8 COMPARE WITH FIG. 4. THE XBT VALUES HAVE BEEN CHANGED BY EXTRAPOLATING BACK UP TO THE SURFACE FROM 4 m

From the theoretical and experimental results it is apparent that the measurement discrepancy will be significant down to 4 m depth. For a historical data base, the XBT records can be extrapolated back to the surface from 4 m by using the slope between 6 and 4 m. This should give, on average, a surface value well within ±0.5°C of the true value except in unusual cases. In stratified conditions, the surface value will usually be underestimated. For the 107 XBT records considered, the mean difference between the surface values of the XBTrecords and those from the thermistor at 5 cm depth was reduced from 0.7° to -0.08°C, both with a probable error of 0.6°. Six percent of the records were individually corrected manually when extrapolation gave unreasonable results.

This correction would be made less drastic if the XBTs were equilibrated to nearly the sea-surface temperature before launch. This might be done in a water bath fed from a sea intake. The XBTs would be left in their protective plastic bags while in the bath or any equilibrium gained would be lost by evaporative cooling of the wet thermistor bead during launch.

The present generation of operational weather satellites (TIROS.N, NOAA6) have a ground resolution of 1 km and 0.2°C in the infrared images. For correlation of ship-based measurements with the infrared data, a continuously immersed thermistor in a body such as the "cappello" should be used, rather than XBT surface values. Correcting the XBTs by extrapolation left a scatter in the data of three times the sensor precision.

To delineate features such as fronts and eddies, the satellite data may be incorporated with XBT values at 4 m, where the precision of the two methods is about equal. The absolute values will be biased, but the strength of horizontal gradients should be preserved. There may be a small lateral displacement (< 1 pixel or 0.5 km) of the front in the direction of its downward slope.

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